

IMPREGNATED NETS OR DDT RESIDUAL SPRAYING? FIELD EFFECTIVENESS OF MALARIA PREVENTION TECHNIQUES IN SOLOMON ISLANDS, 1993–1999

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Abstract. The incidence of malaria in Solomon Islands has been decreasing since 1992. The control program used a combination of methods including DDT residual house spraying and insecticide-treated mosquito nets. To determine how much each method contributed to malaria control, data were analyzed on monthly incidence and on control activities for 41 of 110 malaria zones over the same time period (January 1993 to August 1999). After correction for endogeneity, then spraying, insecticide treatment of nets, and education about malaria are all independently associated with reduction in incident cases of malaria or fever, while larviciding with temephos is not. The evidence suggests that although impregnated bed nets cannot entirely replace DDT spraying without substantial increase in incidence, their use permits reduced DDT spraying. The paper shows that non-experimental data can be used to infer causal links in epidemiology, provided that instrumental variables are available to correct for endogeneity.

INTRODUCTION

The incidence of malaria in Solomon Islands decreased by 67% between 1992 and 1999.¹ Was this decrease the result of the control program or external environmental factors? If the control program can be demonstrated as effective, the next task is to evaluate the relative effectiveness of each method.

Standard epidemiologic approaches to the evaluation of health interventions call for randomized, placebo-controlled, prospective studies of prevention or control methods tested individually or comparatively. The ideal approach may not be possible once certain interventions or mixtures of interventions have become standard practice within the control program. An alternative approach is to apply appropriate statistical methods to analyze non-experimental data retrospectively. Provided that the pitfalls of non-experimental data analysis can be avoided, this approach can shed more light on the effectiveness of interventions under operational conditions. We have applied this non-experimental approach to the analysis of malaria prevention and control methods used from 1993 to 1999 in the Solomon Islands.

Malaria in Solomon Islands before 1992. The Solomon Islands (Figure 1) is an island nation located northeast of Australia with a population of 409,000 (figure from the November 1999 census). The country is divided into 10 administrative units (nine provinces and Honiara City). One province, Rennell-Bellona, is malaria free. Malaria is transmitted by mosquitoes of the *Anopheles punctulatus* group. The entomologic inoculation rate (number of potentially infectious bites per person per year) varies widely over quite small areas. For example in North Guadalcanal, inoculation estimates ranged from 11 to 1,022 infective bites per year for six villages located within an 18 km-radius.²

In the 1960s, the country was divided into malaria zones with approximately 1,500–5,000 people (except small zones on remote islands).³ Spraying with DDT almost achieved eradication by the mid-1970s,^{4,5} but malaria soon rebounded (Figure 2). After the effectiveness of mosquito nets impregnated with pyrethroid insecticides was demonstrated in the Pacific region,^{2,6,7} this method was adopted on a large scale in 1992.

Malaria prevention and control since 1992. The incidence rates of malaria decreased in all provinces from 1992 to 1999

(Figure 3). Managers in each province decide on the frequency and intensity of the different interventions, which include impregnated mosquito nets, house spraying using DDT, larviciding with temephos (Abate®; American Cyanamid Co., Princeton, NJ) and other agents, health talks and information campaigns, and population surveys to identify and treat cases. The choice of control methods is planned in advance on an annual basis according to provincial needs and preferences, and projected budgets. Because of budgetary shortfalls and supply difficulties, plans were not consistently carried out or schedules slipped behind. Ethnic unrest and a political coup in June 2000 caused a financial crisis and significant disruption to control activities and health services, which has not yet been resolved.

Estimating the effectiveness of control methods. Using monthly data collected from 41 malaria zones in five different provinces from 1993 to 1999, we applied multivariate regression methods to assess the relative impact of permethrin-impregnated mosquito nets, DDT residual house spraying, larval control, and health education on malaria incidence, and adjusted for rainfall and the proportion of population residing near water.

House spraying, mosquito net impregnation, and larval control all rely on the effects of insecticides (DDT, permethrin, and temephos, respectively). Estimating the effect of insecticides required some assumptions about their persistence. Although the recommended interval between DDT house spraying cycles is usually six months, Metselaar⁸ found that the mortality rate of *An. punctulatus* caught in huts sprayed with two grams of DDT/m² decreased from 89% to 67% after six months. Slooff⁹ also demonstrated very little decrease in the mortality rates of either *An. koliensis* or *An. farauti* caught in sprayed huts over a nine-month period. For permethrin, bioassay studies in Solomon Islands found 100% mortality in *An. punctulatus* exposed to a net up to 50 weeks after impregnation.¹⁰ As a conservative estimate, to simulate a decay in insecticide effectiveness, we chose to depreciate the amounts of DDT and permethrin applied by 20% per month. This would mean that the amount applied decays to one-third of its original value after six months.

No studies on temephos persistence have been done in

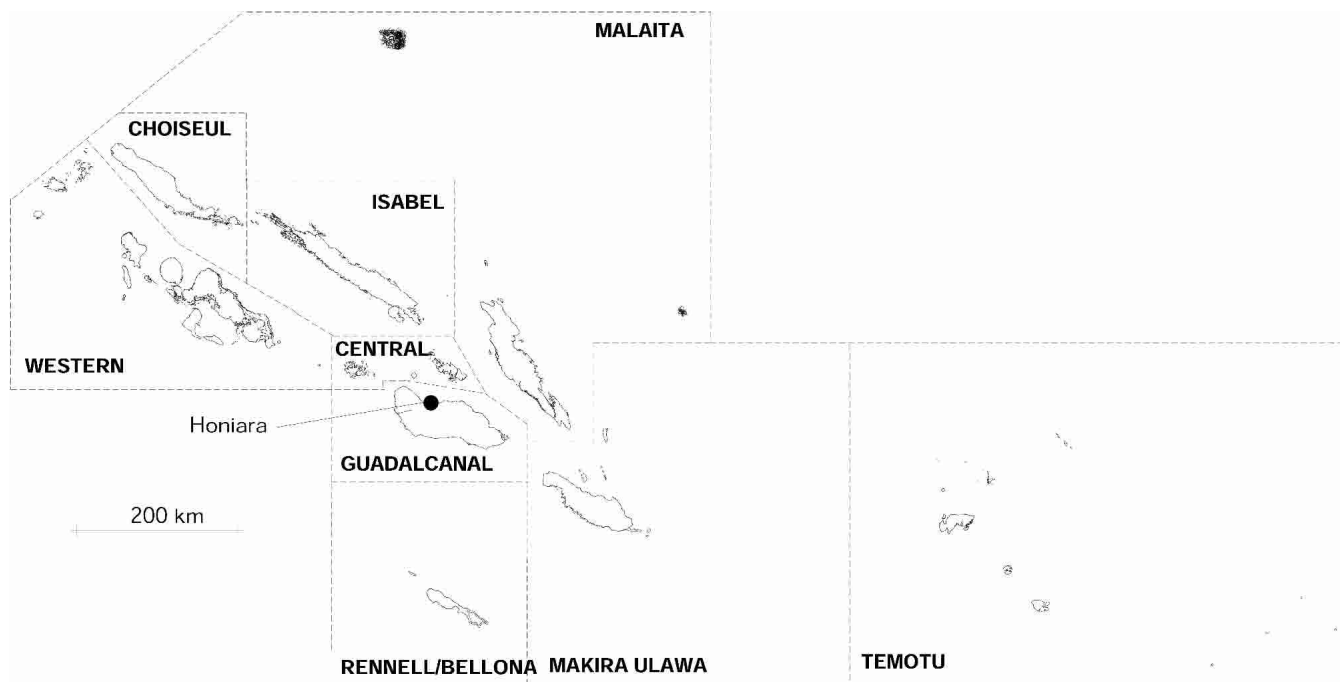


FIGURE 1. Map of the Solomon Islands showing provinces and location of the capital of Honiara.

Melanesia, but in bioassay studies against *Aedes aegypti*, effectiveness decreased from 100% to an average of 33% after 3–5 weeks.¹¹ Therefore, we chose to depreciate the amount of temephos applied by 67% per month.

Untangling the effects of control methods on incidence presents a challenge because of potential endogeneity in the data.¹² Endogeneity describes a situation in which one or more of the supposedly independent variables (e.g., DDT spraying, permethrin impregnation) is determined, in part, by the dependent variable (malaria incidence). This would occur, for instance, if DDT house spraying were done in response to a high incidence of malaria, rather than as a preventive measure in advance of an anticipated peak malaria season. Failure to correct for endogeneity would lead to a biased estimate of the effectiveness of DDT, or even to the conclusion that DDT causes incidence to increase.

The method of correcting for such endogeneity in the data is to apply a technique known as two-stage least squares or

instrumental variable estimation.¹³ In this technique, the potentially endogenous variable is first regressed on the exogenous variables and on a variable known as an instrumental variable. Such an instrumental variable should be correlated with the endogenous variable, but not with the disturbance term. Correcting for endogeneity in this way is frequently done in economic studies, but has been less widely applied in epidemiology.

METHODS AND DATA COLLECTION

Number of cases and incidence of malaria. The eight malaria-endemic provinces are currently divided into 24 regions comprising 110 zones. Data on slide-confirmed malaria cases in all zones are almost complete for the 10-year period 1990–1999. Number of slides examined, numbers of cases of *Plasmodium falciparum*, *P. vivax*, and mixed infections, and total cases by month and zone were extracted from the Vector-Borne Disease Control Program (VBDCP) written records, entered into Epi-Info Version 6.04c (Centers for Disease Control and Prevention, Atlanta, GA), checked, cleaned, and exported to STATA version 6 (Stata Corporation, College Station, TX). Population figures by zone were obtained from the VBDCP.

All health clinics report outpatient cases monthly to the Health Information System (HIS) in Microsoft Access® (Microsoft, Redmond, WA). For 105 clinics in the 41 study zones, data on monthly clinical malaria cases were extracted from the HIS database, exported to STATA version 6, and merged with data on slide-confirmed cases performed for the zones and months under study. Because clinic catchment areas are not contiguous with malaria zones, each clinic was mapped to a zone using the national census data in Map-Info. All except 4 of the 41 zones had at least one clinic; the maximum number of clinics in a zone was 6. Starting in mid 1995, the clinic

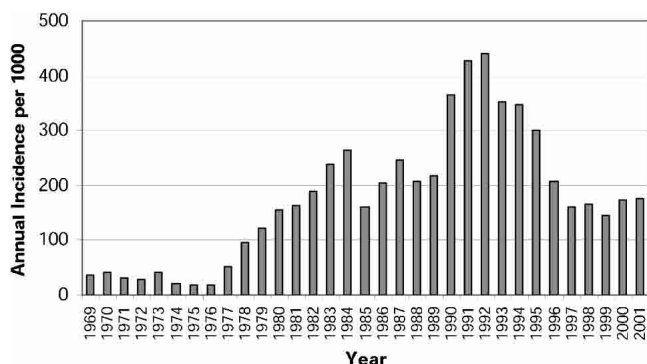


FIGURE 2. Annual incidence of slide-confirmed malaria per thousand persons in the Solomon Islands, 1969–2001.

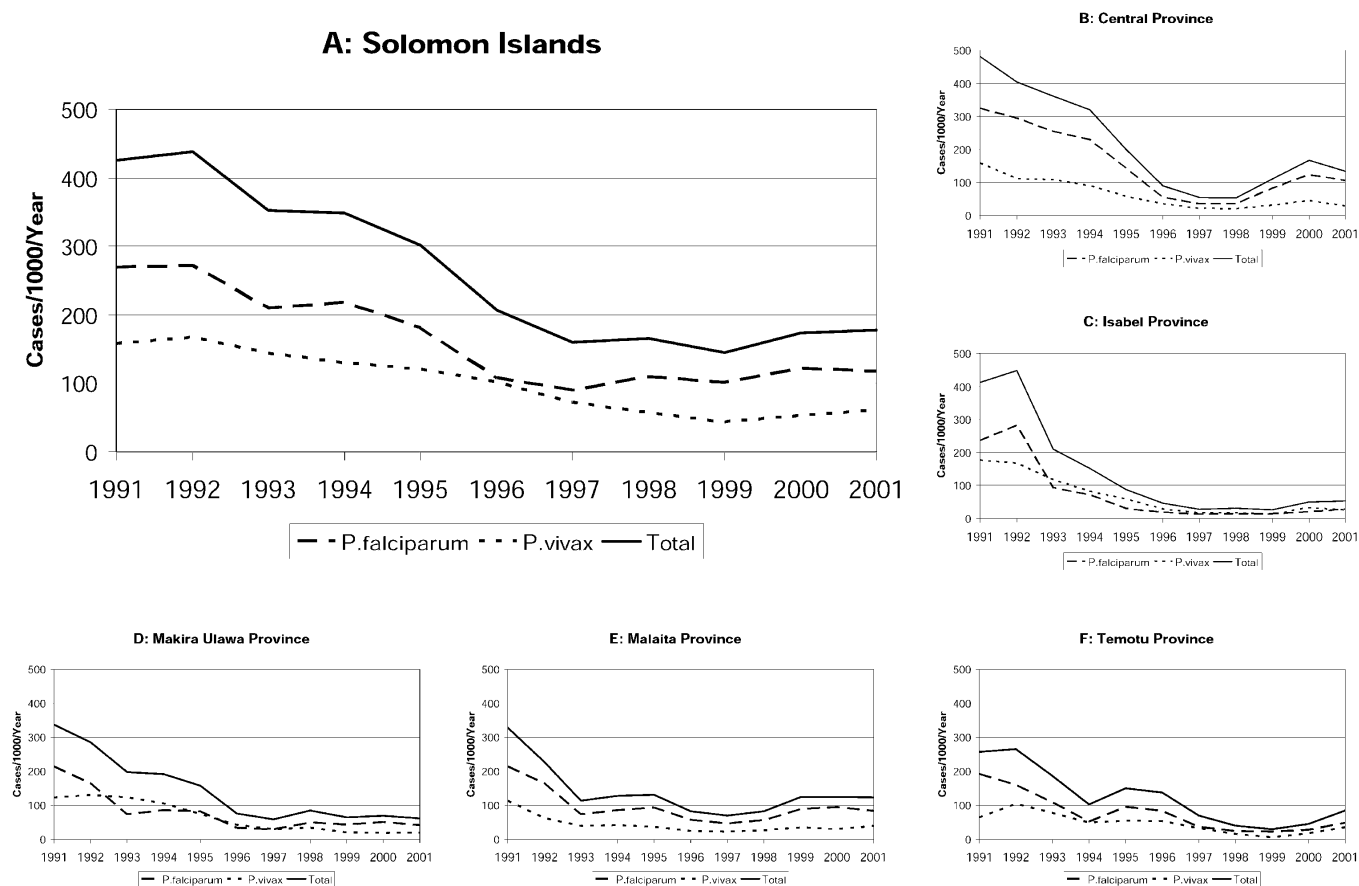


FIGURE 3. Annual incidence of *Plasmodium falciparum*, *P. vivax*, and total case of slide-confirmed malaria per 1,000 persons in the Solomon Islands and in selected provinces included in this study, 1991–2000. **A**, Solomon Islands; **B**, Central Province; **C**, Isabel Province; **D**, Makira Ulawa Province; **E**, Malaita Province (central and eastern regions); **F**, Temotu Province.

report form was modified to include malaria as a subset of total fever cases. Because this category was introduced part-way through our study period and there was variation by clinic on how this category was completed, we used the maximum value of either malaria or fever as our measure of fever cases by clinic and month.

Prevention and control activities. Records of control activities were available for 41 of the 110 zones for the period January 1993 through August 1999. Data were entered into Epi-Info version 6.04c, checked, cleaned, and exported to STATA version 6.

The 41 zones studied were in the following provinces: Cen-

tral, Isabel, Makira-Ulawa, Malaita, and Temotu. Numbers of zones per province and population covered are shown in Table 1. In Malaita, data was only available from 10 of the 25 zones in the province. Thus, we have data from five of the nine malaria-endemic areas in the country, representing approximately 31% of the total population.

The amount of permethrin used per month was used to summarize the effects of provision of new treated nets and re-treatment of previously owned nets. Where only the number of nets issued or retreated per month was available, the average amount of permethrin used per net was derived by simple linear regression from locations that recorded both

TABLE 1

Slide positivity rates and annual incidence of malaria and fever for the zones studied in the Solomon Islands, by province, at the mid-point of the analysis (1996)

Province	Population studied	No. of zones	Slide positivity rate, %	Annual incidence of slide-confirmed malaria/1,000 persons			Annual fever incidence/1,000
				<i>Plasmodium falciparum</i>	<i>P. vivax</i>	Total	
Central	20,399	4	13.9	47.5	31.6	79.1	629.3
Isabel	15,499	9	8.9	22.4	35.8	58.2	616.0
Makira-Ulawa	30,770	12	17.8	34.3	46.0	80.3	325.2
Malaita	45,328	10	23.1	89.5	47.1	136.6	642.4
Temotu	14,855	6	28.8	104.8	67.2	171.8	500.7
Total	126,852	41	19.3	63.0	45.3	108.2	543.5

number of nets and amount of permethrin used. DDT house spraying was quantified by the amount of insecticide used in each charge (0.534 kg of 75% DDT wettable powder). Where only the number of houses sprayed per month and zone were available, the amount used per house was estimated from zones recording complete data by the regression method as described above for permethrin. Abate® (temephos) was quantified as the number of liters used per zone and month.

The amounts of DDT, permethrin, and temephos used were depreciated monthly, as discussed in the Introduction. New amounts applied each month were added to the depreciated amounts present from previous months.

Health education activities, usually provided on a group basis, were quantified as the number of villages visited in a given zone and month.

Geographic variables. Rainfall data by month for January 1993 to August 1999 was obtained from the Meteorological Office for stations located in the provinces of Choiseul (Taro Station), Makira-Ulawa (Kira Kira Station), Malaita (Auki Station), Western (Munda Station), and Temotu (Lata Station) and from two stations in Guadalcanal Province (Honiara City and Henderson Airport). Since Isabel province had no official rainfall station, we used the mean rainfall from Taro and Munda stations for west Isabel zones and the mean rainfall from Auki and Honiara stations for east Isabel zones. We used rainfall data from the nearby Henderson Airport Station on Guadalcanal for the Central province zones.

Proximity to water, estimated as the proportion of the zone population residing within 0.5 km of water, was obtained from the Village Resources Survey database conducted by the Department of Development Planning. Because the terrain in Solomon Islands involves steep volcanic hills, this variable is a surrogate both for altitude and proximity to the coast, as well as proximity to fresh water.

ANALYSIS

Data on malaria and fever cases and on malaria control activities were merged by matching on a unique zone/month variable, resulting in 2,952 observations from 41 zones over 80 possible months of observation (January 1993 to August 1999).

Ordinary least squares, instrumental variable regression, and cross-sectional time series regression analyses were performed using the *reg*, *ivreg*, *xtreg*, and *xtivreg* procedures in STATA version 7.0. Squared terms were introduced for the permethrin, education, and rainfall variables to account for non-linearity in the relationships. To account for the different zone sizes, the zone population at the midpoint of the analysis (1996) was introduced as an independent variable. In addition to current rainfall, a one-month lag of rainfall was included to account for larval development time and parasite incubation period.

RESULTS

Descriptive statistics. The incidence of malaria by species and province from 1991 to 2001 is shown in Figure 3. At the midpoint of the analysis (1996), the average malaria incidence by province ranged from 59.9 to 171.8 cases per 1,000 persons per year (Table 1). The proportion of cases represented by *P.*

falciparum varied from 38.4% in Isabel Province to 65.7% in Malaita Province.

The ratio between fever and confirmed malaria cases was 4.9 to 1 overall, but varied by province, from 3.1 to 1 in Temotu to 10.8 to 1 in Isabel. Some factors possibly accounting for the different ratios are variability in the coverage of diagnostic facilities and in level of suspicion of malaria by clinical staff.

Examples of the location of zones and major health clinics are shown in Figure 4, which illustrates Makira-Ulawa province. The non-depreciated amounts of chemicals added by zone and month are shown in Table 2, together with other variables.

Regression analysis. Two different dependent variables were used. The main regression analysis was performed using the total number of confirmed malaria cases by zone and month as the dependent variable. Variability in zone population size was accounted for by inclusion of the variable zone population at the mid-point of the analysis (popmidz) as an independent variable. We also explored the effect of using the number of fever cases per month in a zone as an alternative dependent variable.

There were two categories of independent variables. The first category was those related to interventions against malaria: DDT, permethrin, temephos and education (all as cumulated depreciated amounts), as well as permethrin² and education². The second category comprised variables unrelated to control activities: rainfall, rainfall², lagged rainfall (one month), lagged rainfall², zone population, and population living within 0.5 km of water. In addition, we included a variable sequential month number (seq.) to represent a time trend.

Regression results are shown in Tables 3 and 4. The first column in Table 3 (model 1) demonstrates the results obtained when only zone fixed effects, rainfall, and time trend are included (no intervention variables). Together, these variables explain 58% of the variation in confirmed malaria cases. The coefficient for rain is positive while that for rainfall² is negative, indicating that more rain increases malaria incidence up to a certain level, above which it decreases incidence.

Adding the intervention variables to the regression (model 2 in Table 3) shows that they contribute substantially to explaining the pattern of changes in incidence. It can be seen that the regression coefficients are negative for the variables permethrin, temephos, and education, indicating that, as expected, use of these methods is associated with decrease in malaria incidence. For the DDT spraying variable, the regression coefficient is positive and highly significant. This indicates either that spraying makes malaria worse (unlikely based on all previous data on spraying) or that spraying is endogenous (spraying occurs in response to higher incidence of malaria).

To investigate further the apparently perverse relationship between spraying and incidence, we used a set of dummy variables representing the calendar month as instrumental variables. The required characteristics of an instrumental variable are that it affects whether the intervention occurs, but does not directly affect the outcome.^{12,13} Once rainfall is controlled for, there is no reason to suppose that calendar month directly affects incidence. Spraying, on the other hand,



FIGURE 4. Map of Makira Ulawa Province showing the location and numbers of malaria zones, major health clinics, and the road (dark line). The provincial hospital and rainfall station are located in the capital of Kira Kira.

is affected by calendar month due to the constraints of the budget cycle and to vacation schedules of personnel.

Results of the regression with instrumental variables are shown in model 3, Table 3. This analysis yields a more plausible estimate of the impact of spraying, which now has a negative coefficient. Permethrin and education remain significantly associated with reduction in incidence, while larval control with temephos does not. The hypothesis that inter-

ventions have no effect is rejected at better than a significance level of 10^{-4} .

The final column (model 4) of Table 3 applies a random effects model to introduce two variables, population and proximity to water, which in this data are constant within zone. Neither here nor for the rest of the models to be discussed does the Hausman test reject the hypothesis that the zone-specific effects can be treated as random.¹³ Including the

TABLE 2
Descriptive statistics for the independent variables, by zone and month

Variable	Number of observations	Mean	SD	Minimum	Maximum
Permethrin (liters)	2,460	0.97	3.39	0	44.4
DDT (kg)	2,461	6.4	32.5	0	644.0
Temephos (liters)	2,461	0.33	1.15	0	15.04
Education visits (no. of villages)	2,277	0.61	3.65	0	65
Rainfall (mm) (from 7 stations)	536	242.2	159.1	4.6	930.9
Zone population in 1996	41	3,045	2,507.2	60	9869
% of population living ≤ 0.5 km from water	41	38.7	26.4	0	82.9

TABLE 3

Regression results for the outcome “confirmed malaria cases” using fixed and random effects models, with and without an instrumental variable*

Outcome variable Type of model	Model 1 Confirmed malaria cases Fixed effects, no interventions	Model 2 Confirmed malaria cases Fixed effects	Model 3 Confirmed malaria cases Fixed effects, instrumented	Model 4 Confirmed malaria cases Random effects, instrumented
DDT		0.42 (11.34)†	−1.589 (3.64)†	−1.62 (3.58)†
Permethrin		−2.108 (5.96)†	−1.637 (3.10)†	−1.12 (2.05)‡
Permethrin ²		0.031 (2.90)‡	0.014 (0.86)	0.004 (0.27)
Temephos		−4.221 (5.11)†	−0.21 (0.14)	−0.124 (0.09)
Education		−1.333 (4.38)†	−1.785 (3.91)†	−1.697 (3.67)†
Education ²		0.019 (3.36)†	0.026 (3.05)‡	0.025 (2.87)†
Proximity to water				0.142 (0.85)
Zone population				0.022 (8.95)†
Rainfall	0.054 (3.63)†	0.06 (4.28)†	0.051 (2.48)‡	0.046 (2.15)‡
Rainfall ²	−4.9 × 10 ^{−5} (2.54)‡	−5.4 × 10 ^{−5} (2.90)†	−5.2 × 10 ^{−5} (1.9)	−4.5 × 10 ^{−5} (1.62)
Lagged rainfall	0.019 (1.28)	0.024 (1.68)	0.018 (0.87)	0.013 (0.61)
Lagged rainfall ²	−7.9 × 10 ^{−9} (0)	−4.5 × 10 ^{−6} (0.24)	−2.2 × 10 ^{−6} (0.08)	−7.7 × 10 ^{−6} (0.27)
Seq.	−0.496 (12.85)†	−0.19 (4.58)†	−0.729 (5.56)†	−0.762 (5.60)†
Constant	40.6 (11.95)†	18.595 (4.97)†	122.323 (0)	53.191 (2.68)†
No. of observations	2,160	2,610	2,610	2,610
Permethrin χ^2 (P)		28.1 (P < 0.0001)§	23.8 (P < 0.0001)	14.4 (P = 0.0007)

* Absolute values of t-statistics are in parentheses. Seq. = sequential month number.

† P < 0.01.

‡ P < 0.05.

§ In Model 2 only joint tests are F-tests.

population variable in models 4 through 7 improves the interpretability of the results by adjusting the estimated effects for the number of people in a zone.

The association of malaria incidence with permethrin is smaller than in the fixed effects model 3, but remains statistically significant. The last lines of Tables 3 and 4 report the joint test that both permethrin coefficients are zero. In all but one of the seven models, we reject the hypothesis that bed nets have no effect at the significance levels of 0.01 or below.

The models shown in Table 4 explore the effects of 1) using fever instead of confirmed malaria as the dependent variable and 2) removing the time trend variable. For ease of comparison, we repeat in the first column of Table 4 the results of the random-effects instrumented model 4 from the last column of Table 3. Compare this with model 5 in Table 4, which shows the results when the dependent variable is fever rather

than confirmed malaria. The results are similar but the effect of education is no longer statistically significant when the outcome fever is used, and larviciding now appears to have a positive association with fever. On the other hand, in this model and also in model 7, proximity to water is a statistically significant predictor of fever. It is possible that this variable predicts fever cases better than confirmed malaria cases because proximity to water is associated with multiple causes of fever, not just with malaria.

In the last two columns of Table 4, we demonstrate the effects of removing the time trend variable from the model, with confirmed malaria (model 6) or fever (column 7) as the outcome. Presumably because spraying, permethrin use, and education have all been correlated with time, removing the time trend uncovers a stronger impact of all three of these interventions, with coefficients substantially larger than in the

TABLE 4

Results for the outcomes confirmed malaria cases or fever cases using random effects models, with and without a time trend variable*

Outcome variable Type of model	Model 4 Confirmed malaria cases Random effects, instrumented, with time trend	Model 5 Fever/suspected malaria cases Random effects, instrumented, with time trend	Model 6 Confirmed malaria cases Random effects, instrumented, without time trend	Model 7 Fever/suspected malaria cases Random effects, instrumented, without time trend
DDT	−1.62 (3.58)†	−5.028 (3.96)†	−2.544 (3.29)†	−6.622 (3.44)†
Permethrin	−1.12 (2.05)‡	1.693 (1.07)	−2.918 (4.22)†	−4.751 (2.63)‡
Permethrin ²	0.004 (0.27)	−0.066 (1.4)	0.043 (2.06)‡	0.067 (1.28)
Temephos	−0.124 (0.09)	8.614 (2.30)‡	0.421 (0.23)	7.302 (1.65)
Education	−1.697 (3.67)†	−1.74 (1.33)	−3.085 (4.34)†	−5.41 (3.06)†
Education ²	0.025 (2.87)†	0.006 (0.26)	0.05 (3.75)†	0.066 (2.12)
Proximity to water	0.142 (0.85)	1.482 (2.71)†	0.19 (1.07)	1.55 (2.62)†
Zone population	0.022 (8.95)†	0.071 (10.54)†	0.026 (7.22)†	0.08 (9.04)†
Rainfall	0.046 (2.15)‡	0.145 (2.30)‡	0.075 (2.67)†	0.24 (3.14)†
Rainfall ²	−4.5 × 10 ^{−5} (1.62)	−1.4 × 10 ^{−4} (1.68)	−1.1 × 10 ^{−4} (2.84)†	−3.4 × 10 ^{−4} (3.27)†
Lagged rainfall	0.013 (0.61)	0.012 (0.19)	0.045 (1.58)	0.108 (1.42)
Lagged rainfall ²	−7.7 × 10 ^{−6} (0.27)	1.0 × 10 ^{−4} (1.26)	−5.5 × 10 ^{−5} (1.42)	−9.8 × 10 ^{−5} (0.99)
Seq. month	−0.762 (5.60)†	−2.841 (6.53)†		
Constant	53.191 (2.68)†	162.351 (2.52)‡	43.16 (1.92)	84.837 (1.26)
No. of observations	2,610	2,338	2,610	2,338
Permethrin: χ^2 (P)	14.4 (P = 0.0007)	2.1 (P = 0.35)	25.9 (P < 0.0001)	10.2 (P = 0.01)

* Absolute values of t-statistics are in parentheses. seq. = sequential month number.

† P < 0.01.

‡ P < 0.05.

other models with the same dependent variable. For the simulations reported below we use model 6.

Figure 5A shows the effect predicted by model 6 of rainfall and lagged rainfall on malaria cases per zone per month, with a 95% confidence interval. Figure 5B shows the predicted effect on malaria cases per zone and month, with 95% confidence intervals, of each intervention method. Similar graphs drawn for the outcome fever would have larger confidence intervals.

The number of confirmed malaria cases observed is an underestimate of the actual number occurring, since many do not reach health facilities. For this reason, we also used fever cases as an outcome in regression model 7, but fever case

numbers are obviously an overestimate of malaria cases, since they included many other non-vector-borne and vector-borne diseases. Because of the measurement error it introduces into the outcome, using the fever data is not suitable for drawing detailed causal inferences, but the coefficients in model 7 may be regarded as an upper bound of the potential effects of the interventions on malaria. In model 7, the coefficients for DDT (-6.622), permethrin (-4.741), education (-5.41), and rainfall (0.245) are all larger than in model 6.

The parameter estimates of model 6 allow us to ask how effectively impregnated bed nets can substitute for the other interventions under operational conditions in the Solomon Islands. Under the assumption that the other variables in

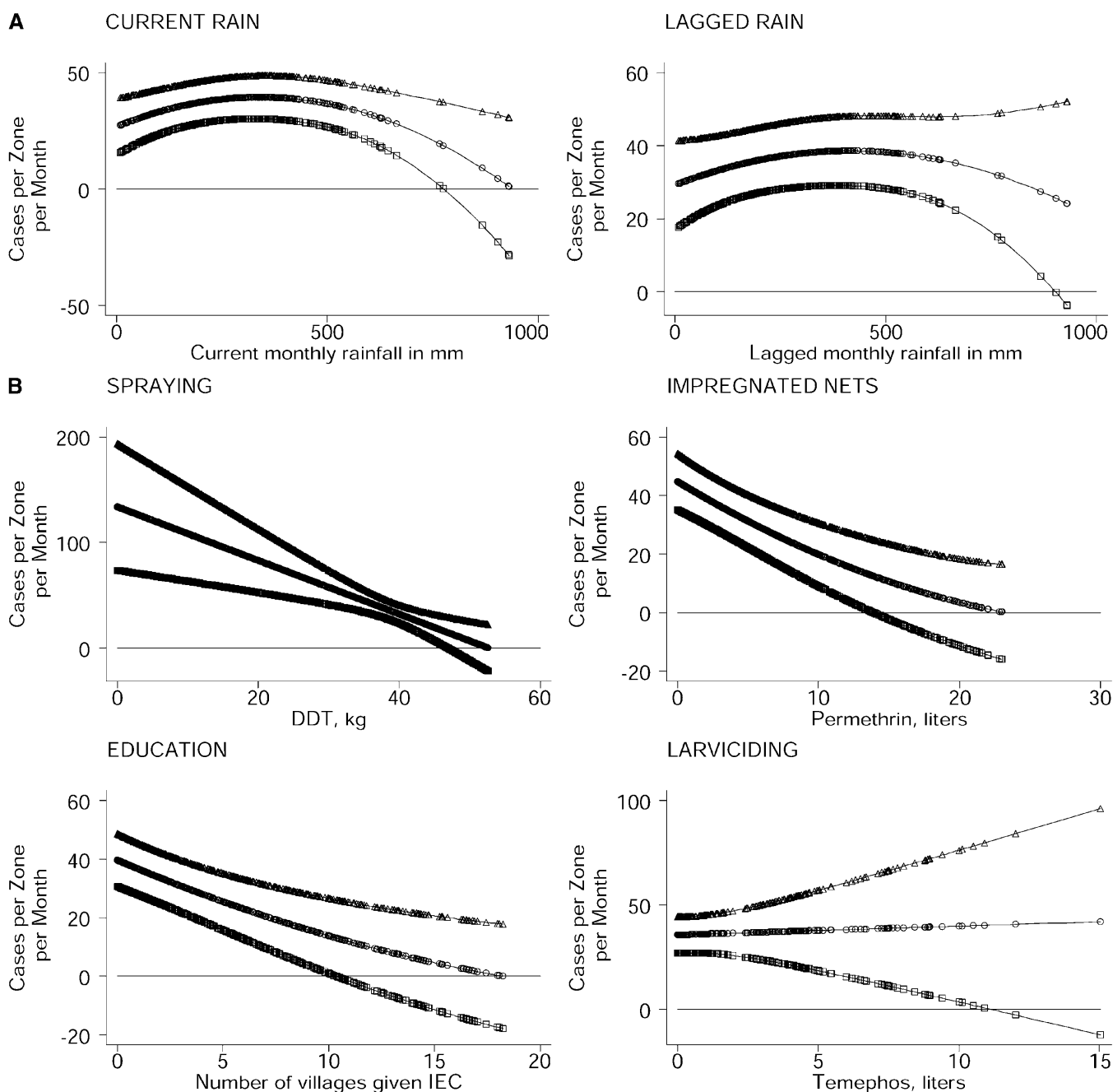


FIGURE 5. Predicted effects of **A**, rainfall and **B**, interventions on malaria cases, using regression model 6 (time trend excluded). IEC = Information, education, and communication.

model 6 are held constant at their means, Figure 6 shows the finding that DDT spraying is substantially more effective than impregnated bed nets in these field conditions. At the sample mean, the program achieved 40 kilograms of DDT per zone per month and 3.6 liters of permethrin and held the average number of cases per zone to 33.6 (or the equivalent of 11.0 cases per 1,000 persons per month). The top curved line shows that increasing DDT application by 50% (from 40 kilograms per zone per month to approximately 60) would reduce incidence to zero, while a six-fold increase in permethrin (from 3.6 liters to approximately 22) would be required to achieve the same result. Furthermore, at 60 kilograms of DDT per month per zone, no permethrin would be required to achieve zero incidence. However, the 22 liters of permethrin would require almost 40 kilograms of DDT to reduce incidence to zero. If the 22 liters of permethrin were applied in the absence of DDT, model 6 estimates that cases would triple from the current level to 100 (or approximately 33 cases per 1,000 persons per month). This last inference is shown in Figure 6 by the intersection of the bottom curved line with a horizontal line representing zero DDT.

DISCUSSION

This report examines a situation in which malaria prevention and control seem to be working and asks why is it working? This is not immediately obvious when different interven-

tions are used at the same time. The Solomon Islands VBDCP has high-quality data on control measures. The large variation in intensity and frequency of control measures by zone presented an opportunity to untangle the effects of different interventions using multivariate regression methods. As far as we are aware, this is the first attempt to estimate effectiveness of control measures from retrospective data where a mixture of interventions has been used. It is also the first report to apply multivariate random-effects regression with instrumental variables to this kind of data.

The results show that DDT spraying, permethrin impregnation of mosquito nets, and educational activities were all independently associated with reduction in malaria cases, while larval control using temephos was not. The associations held even after adjusting for variables such as rainfall and proximity to water. The control methods reduced malaria cases even when a time trend variable (representing unquantified environmental variables operating during the study period) was included in the model.

Other independent variables associated with incidence we were unable to evaluate and control for in this study due to lack of information include but are not limited to geographic factors (average altitude, roads, proximity to a town); social factors (educational levels, access to cash for transport to clinic); health system factors (time to a health facility); and control program factors (relative allocation of funds and staff between zones, timing of resource delivery).

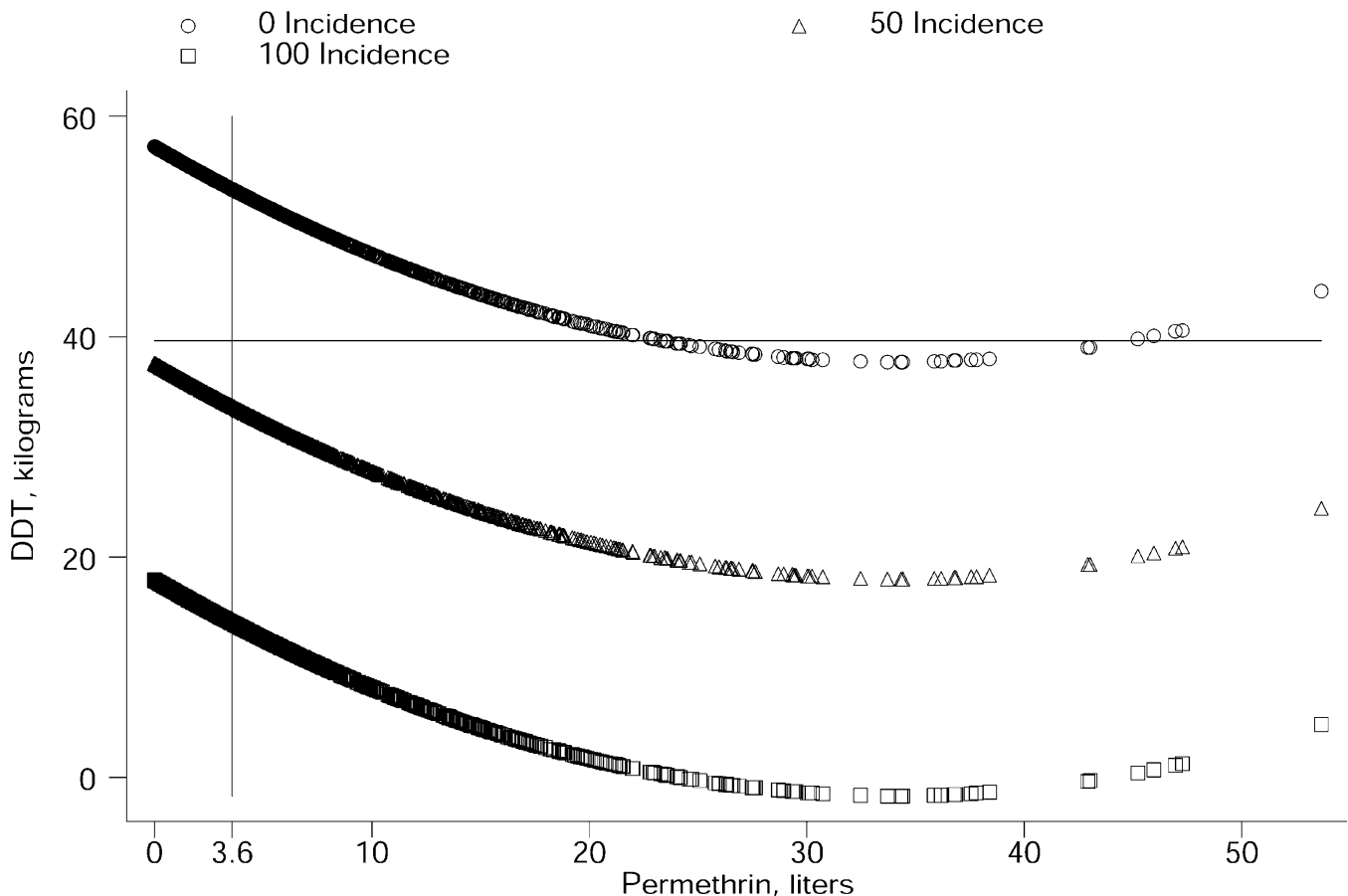


FIGURE 6. Combination of accumulated sprayed DDT and accumulated applied permethrin that lower malaria incidence to three specific levels given that other variables are held at their mean levels (computed from model 6 of Table 4).

Previous research in Solomon Islands has compared DDT house spraying with impregnated nets in an attempt to determine which method is better, on the assumption that only one method would be chosen.^{2,14,15} The results from the current study suggest that both methods, together with educational activities, have been contributing to the slow decrease in malaria incidence in the Solomon Islands, and that the decrease would have been even slower if only one method had been used. Residual house spraying remains an effective option for malaria control, despite claims that it has lost its effectiveness due to the evolution of behavioral resistance in the main vector species *An. farauti*.¹⁶ Estimates of the synergy between spraying and permethrin (not reported here) suggest that the benefit of either is somewhat reduced in the presence of the other, but the interaction effect is not statistically significant.

Malaria exerts a large toll on the health of Solomon Islanders, with detrimental consequences on the ability to work or attend school.¹⁷ Previous studies in the country on the cost-effectiveness of bed nets versus spraying were used to support national policy on impregnated mosquito nets.¹⁸ The current study will provide improved data on the comparative effectiveness of these methods, which can be combined with unit cost estimates for each method to guide policy toward the most cost-effective combination of interventions. Such data are badly needed to determine the cost-effectiveness of malaria interventions, particularly packages of interventions.¹⁹

A recent review suggested that pyrethroid-treated nets were as effective for malaria control as house spraying with DDT, malathion, or a pyrethroid,²⁰ while a comparison in South Africa estimated that impregnated nets were more effective but much less cost-effective than house spraying.²¹

The evidence from the current study suggests that impregnated bed nets cannot easily replace DDT spraying without substantial increases in malaria incidence. Rather, it is the role of bed nets and other interventions to permit reduced use of DDT spraying for any given target incidence level (Figure 6). A full economic analysis would have to include not only the program costs of all alternative interventions, but also the environmental benefits of reducing DDT use to arrive at the socially optimal combination of malaria control interventions.

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Disclaimer: The findings, interpretations, and conclusions expressed in this report are entirely those of the authors and do not necessarily represent the views of the World Bank, its Executive Directors, or the countries they represent.

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